

FINAL REPORT

Title: Assessing the Impacts on Smoke, Fire and Air Quality Due to Changes in Climate, Fuel Load and Wildfire Activity Over the Southeastern U.S.

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List of Abbreviations/Acronyms

AAB – annual area burned
AR5 – Fifth Assessment Report
CESM – Community Earth System Model
CFFDRS – Canadian Forest Fire Danger Rating System
CMAQ – Community Multiscale Air Quality (model)
CONUS – continental U.S.
CTM – chemistry-transport model
CWD – coarse woody debris
DGVM – dynamic global vegetation model
FCCS – Fuel Characteristic Classification System
FSB – Fire Scenario Builder
FWI – fire weather index
GCM – general circulation model
GHG – greenhouse gas
GIS – Geographical Information Survey
GISSE – Goddard Institute of Space Studies Model E2
hPa – hectoPascal (pressure unit)
HI – Haines Index
IPCC – Intergovernmental Panel on Climate Change
NAAQS – National Ambient Air Quality Standards
PM – particulate matter
PM_{2.5} – particulate matter below 2.5 µm in aerodynamic diameter
PNW – Pacific Northwest Station, USDA Forest Service
RCP – Representative Concentration Pathway
SMOKE – Sparse Matrix Operations Kernel Emissions (processing system)
SRS – Southern Research Station (SRS), USDA Forest Service
UNC-IE – University of North Carolina—Institute for the Environment
USFS – U.S. Forest Service
WRF – Weather Research and Forecasting (model)

Keywords

Climate change, wildfire emissions, air quality, fuel load projections

Acknowledgements

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Abstract

An issue of great concern on federal lands is wildland fires, which have increased in frequency and strength over the past few decades as a possible consequence of climate change. Modeling wildfires under an evolving climate is challenging: there are disparate spatial and temporal scales involved in characterizing wildfire emissions and their effects on ambient air quality and visibility downwind, and in forecasting changes in vegetation and fuel loads in response to the changing climate and resulting changes in fire regimes. Many models altogether ignore these changes in future climate regimes, giving rise to large uncertainties in predicting future climate impacts on fires, air quality and compliance with the National Ambient Air Quality Standards (NAAQS). This project sought to address some of the issues underlying the reliable projection of fire emissions and air quality in an evolving climate, through a regional-scale modeling study over the Southeast involving an ensemble of regional climate simulations that provide mesoscale meteorological inputs to determine fire weather and estimate wildfire emissions and their air quality impacts in a number of time slices sampled from a historical decade (1996-2005), and a mid-century decade (2041-2050).

The project objectives are to: (a) examine methods for downscaling climate variables for predicting fire weather reliably over the Southeast to capture the years with the lowest and highest expected fire occurrences; (b) use the downscaled meteorology to project fuel loads and fire activity in the representative future years to estimate future-year fire emissions, and (c) examine the air quality impacts of these emissions relative to the National Ambient Air Quality Standards (NAAQS) over the Southeastern U.S., using a multiscale chemistry-transport model (CTM) of criteria pollutants, e.g., O₃, particulate matter (PM), and NO₂.

The project used dynamical downscaling of climate from two general circulation models (GCMs), the NASA GISS and NCAR/DOE CESM, for years selected from a historical decade and a future decade under two Representative Concentration Pathways defined by the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5). The 12 years selected represented high and low fire potential years in each decade, for each RCP and GCM. This ensemble defined the meteorology needed to calculate a daily fire weather metric and fire activity using the Fire Scenario Builder, and thus estimate wildfire emissions using the BlueSky fire emissions model over the Southeast. These emissions were combined with those for other natural and anthropogenic source sectors to drive the Community Multiscale Air Quality Model (CMAQ). Fuel change from the historical to future decade was estimated using a simple ratioing of future/historical live biomass in three carbon pools, leaf, litter and coarse woody debris (CWD), and applying the ratio to existing fuel loads for 1996-2005 in the Fuel Characteristic Classification System (FCCS), which provides fuel load inputs to BlueSky.

The study found that the regional climate modeling improves the representation of terrain and the localized warming and drying associated with the downslope flow off the Appalachian Mountains for the upper temperature extreme change. The greatest fuel tonnage appears to be in the leaf and CWD pools and concentrated in the Appalachian region. Given the warming and drying predicted in some of the ensemble regional climate simulations, this would be a region for increased fires in the future decade. Overall, this work is relevant to air and forest resource managers who need to prepare plans that include any future period, and atmospheric scientists in need of ensemble model results for the Southeast (our results will be archived in the Forest Service Research Data Archive by the end of this year).

Objectives

The objectives of our project as stated in our proposal are:

1. Examine methods for downscaling climate variables for predicting fire weather reliably over the Southeastern U.S. using Representative Concentration Pathways (RCPs) specified by the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) to capture the years with the lowest and highest expected fire occurrences.
2. Use the downscaled meteorology to project fire activity and fuel loads in the representative future years to estimate future-year fire emissions.
3. Examine the air quality impacts of these emissions relative to the National Ambient Air Quality Standards (NAAQS) over the Southeastern U.S., using a multiscale chemistry-transport model (CTM) of criteria pollutants, e.g., O₃, particulate matter (PM), and NO₂.

Through a series of simulations this study was aimed at testing the following hypotheses: (1) there are significant changes in wildfire emissions due to changes in fire weather and fuel loads, which can be correlated to changes in future meteorology; (2) representing the spatial and temporal variability of wildfires results in significantly different impacts on future-year air quality than assuming a constant spatial-temporal distribution, and (3) these differences can be quantified and used to support air and land management

Due to the departure from the University of key project personnel, including two co-PIs (Shankar, Bowden), a key emissions modeler (Omary) and the lead terrestrial ecologist (Ran), before project completion, and the fact that no new personnel were hired to fulfill their functions within the project duration, we were unable to finish the emissions modeling with modified fuel loads, and the future-year air quality modeling (parts of Objectives 2 and 3). We did complete all the meteorological modeling and the emissions modeling for fixed fuel loads for the twelve years selected for this study, and the air quality modeling for two of those years, representing the historical period 2000-2010. Emissions generated in this project accounted for climate change impacts on fire activity (fire weather). Software development to project fuel loads was also completed, but the emissions modeling to assess the impacts of fuel load change on wildfire emission magnitudes is still pending.

Background

An issue of great concern on federal lands is wildland fires, which have increased in frequency and strength over the past few decades as a possible consequence of climate change. Modeling wildfires under an evolving climate is challenging. There are disparate spatial and temporal scales involved in characterizing wild fire emissions and their effects on ambient air quality and visibility downwind, and in forecasting changes in vegetation and fuel loads in response to the changing climate and resulting changes in fire regimes. Many models altogether ignore these changes in future climate regimes, giving rise to large uncertainties in predicting future climate impacts on fires, air quality and compliance with the NAAQS.

Regional assessments of wildfire occurrence and impacts under climate change suffer from a disparity of spatial-temporal scales in reliably estimating the meteorological variables of relevance. These need to be predicted over multiple decades over large spatial extents to capture the changes in synoptic circulations, and at a sufficiently fine spatial scale to characterize the variability in fuel loads and fire weather. Downscaled modeling studies are a cost-effective way to address some of these disparities, and improve understanding of the consequences of climate change for wildfire occurrence and their effects downwind on ambient pollutant loads. We chose the Southeastern domain for our study because although the Southeast does not experience the magnitude of wildfires seen in the Western U.S., it has more heavily populated areas that are in close proximity to wild lands, and thus merits region-specific modeling to quantify air quality and its potential health impacts in future climate regimes. Fifteen cities in the Southeast were estimated in the 2011 Census to have populations exceeding 400,000. Expected exceedances of the NAAQS in these metropolitan areas under a changing climate could be exacerbated by wildfires as a result of the rapid growth expected in the coming decades.

In this report we describe a modeling and analysis study focused on the Southeastern U.S., an area in which management of fire and air quality is already challenging today, to address some of the issues underlying the reliable projection of fire emissions and air quality in an evolving climate,

The University of North Carolina—Institute for the Environment (UNC-IE) led the project. Significant in-kind support was provided on projecting fuels and fire activity through no-cost collaborations with Dr. Donald McKenzie, a research ecologist at the Pacific Northwest (PNW) Station, and Dr. Jeffrey Prestemon, a research forester at the Southern Research Station (SRS) of the U.S. Forest Service (USFS).

Materials and Methods

In this section we describe methods, models and analysis tools used for our study. Figure 1 shows a schematic representation of the various models and databases used to generate the wildfire emissions inventories developed in this study. The modeling domain is shown in Figure 2.

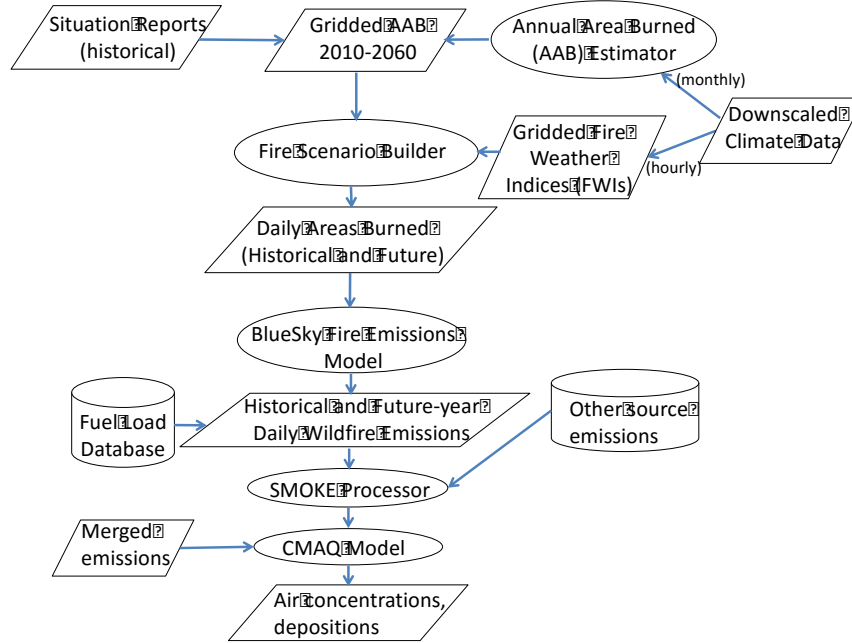


Figure 1. Flow diagram of various models and data needed for projecting future wildfire emissions impacts on air quality.

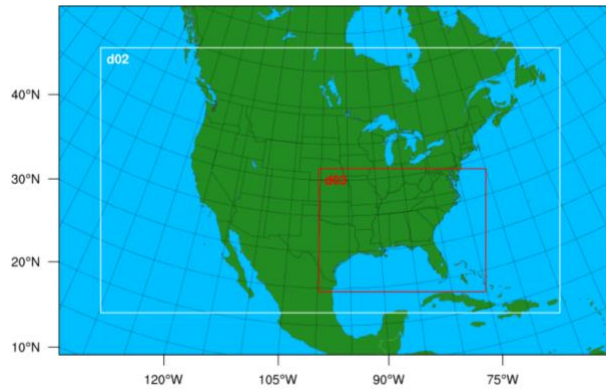


Figure 2. Meteorological modeling domains: The outer-most domain: 108-km x 108-km grid spacing; D01 – Continental U.S. (CONUS) domain at 36-km x 36-km grid spacing; D02 – Southeastern domain at 12-km x 12-km grid spacing.

Our ensemble approach for wildfire projections in the Southeast used two general circulation models (GCMs) representing global-scale changes in climate and vegetation, which were dynamically downscaled over a Southeastern modeling domain using the Weather Research and Forecasting (WRF) model (Skamarock et al., 2008), a mesoscale meteorological model that

provides hourly output of the prevailing weather on the regional scale, under current and future climate scenarios. Future climate was represented in each GCM by two different Representative Concentration Pathways (RCPs) defined in the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC): RCP4.5, representing moderate growth of greenhouse gas (GHG) emissions and a net positive radiative forcing (RF) of 4.5 W/m^2 by the end of the century; and RCP8.5, representing a business-as-usual growth scenario projected to result in an RF of 8.5 W/m^2 by the end of the century. The Haines Index (HI -- Haines, 1988), a composite metric of weather parameters indicating the probability of sustaining wildfires, was used to identify years of high and low fire frequency in a historical (1996-2005) and a future decade (2041-2050) that were selected for downscaling with WRF from archived data for each of the two GCMs and RCPs. This created an ensemble of 12 annual model simulations (RCPs apply only for the projections, not the historical periods). A statistical model that projects annual areas burned (AABs) on the model grid over the Southeast to mid-century (Prestemon et al., 2016) was used to constrain daily gridded acres burned using the Fire Scenario Builder (FSB) model (Stavros et al., 2014; McKenzie et al., 2006) for each of the 12 ensemble members; daily fire weather index inputs for these estimates used the WRF model outputs from the corresponding mesoscale simulation. The daily burned areas were then used in the BlueSky fire emission model (Larkin et al., 2009) to estimate daily point fire emissions that are needed as inputs for air quality simulations. The emissions for the point wildfire sector were merged with those from other major anthropogenic and natural emissions sectors for atmospheric trace constituents, including prescribed and crop waste burning, biogenic, industrial, power generation, agricultural, mobile, ocean and dust sources using the Sparse Matrix Operations Kernel Emissions (SMOKE) processing system (Houyoux et al., 2000). The merged emissions were then used, along with the meteorological inputs to drive the Community Multiscale Air Quality (CMAQ) model (Byun and Schere, 2006), to assess how the air quality impacts of the historical wildfire emissions might change under the various climate regimes.

Fire Weather Index for Dynamical Downscaling

GCMs used for climate change projections typically have resolutions ranging from 100 km to 300 km, and thus do not capture the mesoscale atmospheric circulations that contribute to the Southeast regional climate (i.e., thermal and topographically forced instabilities). Mesoscale models, however, can be used to downscale GCM output dynamically and improve projections of physical processes that are important to represent meteorological changes, especially those affecting extreme events such as wildfires. The computational burden of running mesoscale simulations over the Southeast continually for a decade at a time led to the use of our ensemble approach where representative time slices are selected to allow the examination of fire activity under a range of synoptic circulations, for both historical and future periods.

The selection of the time slices for the ensemble was based on the Haines Index (HI) for fire potential, which combines stability and moisture content of the lower atmosphere. The larger the index the drier and more unstable the air; a maximum value of 6 promotes fire spread and intensity. In a climate context, the HI has been associated with large-scale atmospheric circulation patterns that are resolved by the GCMs, and the interannual variability of wildfires (Trouet et al., 2009). A Haines Index value of 6 is useful for predicting favorable fire weather on average for a given year and the likelihood of these fires becoming large and erratic. We applied the HI for the two selected GCMs, the NCAR/DOE Community Earth System Model (CESM), and NASA Goddard Institute of Space Studies Model E2 (GISSE) to identify years for 8 future,

and 4 historical annual time slices for the mesoscale simulations. We developed a tool that calculated the HI at 00Z each day for a historical (1996-2005) and a future (2041-2050) decade for each GCM and RCP, and counted the number of days in each year that the HI value was at or above 6. Years with the lowest and highest counts were selected from each decade to bracket the uncertainty in the predictions from our modeling ensemble. Table 1 lists the simulation years selected by this process for this study.

Table 1. Years selected for the simulations

GCM	Years with Low/High Fire Potential		
	Historical (1996-2005)	RCP 4.5 (2041-2050)	RCP 8.5 (2041-2050)
NCAR/DOE CESM	2001 / 2005	2050 / 2042	2043 / 2041
NASA GISS Model E2	2001 / 2005	2049/ 2043	2045 / 2043

Annual Area Burned Projections

The statistical model of Prestemon et al. (2016) provide a useful dataset over the Southeast for the proposed simulations in that they build upon historical data of fire activity over the region, in combination with downscaled climate model inputs and socioeconomic factors known to be highly correlated with fire activity in the region to project annual burned areas to mid-century. Using historical fire data to study future-year wildfire impact assessments will be wrong from the start (McKenzie et al., 2014) because they do not account for changes in climate, land use, population density, or income levels (which may affect emissions exposures—e.g., Rappold et al., 2012); all of these factors are regional drivers in initiating and sustaining wildfires (Prestemon and Butry, 2005) as well as in suppressing them (e.g., Butry et al., 2001). The statistical models developed by Prestemon et al. (2016) take into account the combined impacts of climate and socioeconomic factors on wildfire occurrence to estimate AAB at the county level. These models perform multiple regressions of historical AABs onto future projections of downscaled climate, socioeconomic factors and land use change over the Southeast, to project AABs over the next five decades. These statistical models of AAB thus provide a framework for the construction of wildfire EIs that allow air quality management to be based on an evolving landscape of natural and human factors influencing fire occurrence, and to project future air quality in the coming decades more realistically in response to potential changes in climate and society. For the historical years, we used AAB data averaged over 1992-2010 provided by Dr. Prestemon for a different study; for the future time slices, Dr. Prestemon provided the statistical model results of AAB for a representative year, 2045. The Southeastern domain used in Prestemon et al. (2016) differed slightly from the one used in this study. We therefore used an ArcGIS software application to remap those data to our domain.

Fire Scenario Builder

The Fire Scenario Builder model (FSB -- McKenzie et al. 2006) is a stochastic model that estimates daily areas burned at the spatial scales associated with regional climate and air-quality models. The FSB was designed specifically to provide coarse-scale fire areas (as opposed to individual fire perimeters) as input to current and future projections of daily fire emissions and smoke dispersion. Two key assumptions of the FSB are (a) that a fire event in a grid cell will

only occur once in a fire season (assuming that fuels cannot return to the landscape within the season), and (b) that a fire season is entirely contained within the calendar year. Using mean AAB associated with the baseline climatology (in this case the historical, and the 2045 data previously discussed), the FSB samples a fire-start day randomly from the fire season based on an assigned probability distribution of fire likelihood. This is typically uniform unless informed by particular fire-start data. For each model grid cell, the FSB constructs a cumulative distribution of area burned with the AAB for that grid cell as the mean, using a mixed model that is a negative exponential up to the 95th percentile and a truncated Pareto distribution beyond that value. The beginning and end dates of the fire season appropriate for the Bailey ecoregion province (Bailey, 1995) allocated to each model grid cell are read from a national database maintained by the USDA Forest Service. Fires are further constrained to burn only if precipitation is less than 5 mm/day. If it is above that, another fire-start day is sampled.

A fire-weather metric from the historical climatology that can be simulated for the future is chosen as an indicator of potential fire size. The fire-weather metric used in this study is the fire weather index (FWI – Van Wagner and Pickett, 1985) from the Canadian Forest Fire Danger Rating System (CFFDRS). It is a comprehensive metric that incorporates several measures of heat and dryness, and has been used for fire-danger projections (Stavros et al., 2014). It is computed from the dynamically downscaled daily meteorology, both for historical and future years. Area burned on the randomly selected fire-start day for each time slice in our ensemble of simulations is calculated as the quantile from the cumulative distribution of area burned that corresponds to the quantile of the FWI from the climatology for that time slice matching that day's FWI. Fires as treated by the FSB can burn up to 10 000 acres per day; larger fires are modeled as multiday fires.

BlueSky Fire Emissions Model

Using the results from the FSB, daily fire emissions were estimated using the BlueSky smoke emissions modeling framework (Larkin et al. 2009) for each of the cases discussed (historical, statistical, and dynamical). The BlueSky model accomplishes this by 256 using the gridded daily burned areas in conjunction with fuel load data available in the USFS Fuel Characteristic Classification System (FCCS) database (McKenzie et al. 2007). BlueSky is a highly modular framework that links state-of-science models of meteorology, fuels consumption, and emissions, and provides flexibility in the data sources for fire activity and fuel load inputs. Fuels consumption in BlueSky is based on the CONSUME model version 3.0 (Ottmar et al., 2006), the default modeling option, which is an empirical model developed by USFS based on 106 different pre- and post-burn plots covering several vegetation types and fire conditions. Emissions are estimated as daily rates by a fire emissions module for CO, CO₂, CH₄ and PM_{2.5}. In our application BlueSky is used at the latitude-longitude location of each fire strictly for estimating total emission magnitudes of the various emitted species, which are vertically distributed in the air-quality model simulation in a later step (not presented here), using its inline plume-rise calculation.

Fuel Projections

A challenge in projecting fuel load changes in the future is that live biomass loads are not well correlated with downed deadwood even when vegetation is modeled at the plot level. This was the finding of a previous project (EPA STAR Grant RD 83227701-0) in which we used the

Photosynthetic (nitrogen) Evapotranspiration model (PnET) (Aber et al., 1997) to calculate live biomass in a future year using climate model inputs, and attempted to develop a regression model to estimate fuel load inputs to BlueSky from the live biomass. In this study, therefore, we developed a simple ratioing approach to project fuel loads in the future decade using outputs for three carbon compartments from the dynamic global vegetation model (DGVM) that is linked to the CESM; due to the limited availability of data from the GISSE it was not possible to use its DGVM outputs for this exercise. DGVM outputs for carbon mass in leaf, litter, and coarse woody debris (CWD) were downloaded for the historical and future decade and averaged to calculate the future/historical biomass ratio in each carbon pool. These data were rasterized and remapped to the FCCS 1-km x 1-km spatial resolution, with the same ratio applied to all the FCCS grid cells within each DGVM grid cell. The remapped ratios could then be applied to the appropriate fuel categories in the FCCS that belong to each carbon pool, to get an estimate of how the fuel load in that category changed in 2041-2050 relative to 1996-2005. We developed software tools that calculate the gridded carbon ratios over the domain, and apply them to the relevant fuel categories in FCCS. The I/O structure of BlueSky v3.5 that we used in this study is such that the fuel loads are spatially unvarying for a given fuel bed ID, i.e., a given fuel bed ID is assigned the same fuel load data wherever it occurs in the spatial domain. To update the fuel beds with our modified fuel loads for the future decade, we made a minor modification to the BlueSky I/O section that reads the FCCS fuel IDs and their location in the spatial map, and assigns the fuel loads for the various fuel categories in each fuel bed. The implementation only involved a few lines of python code in BlueSky, and no changes to the original FCCS data, i.e., the original fuel loads are modified by applying the future/historical fuel ratios and assigned to the appropriate fuel beds read in from FCCS dynamically, before being used by the CONSUME module. We consider this a major contribution in this project. The data from this software application will be archived along with all other data we generated.

Results and Discussion

The meteorological analysis from the downscaling was done in two ways to examine the differences in mean precipitation (mm) and mean 2-m temperature ($^{\circ}\text{C}$) in the summer (June-July-August) between a future and a historical year: for the biggest expected difference, i.e., future high fire year vs. historical low fire year, and for the smallest expected difference, i.e., a future low fire year vs. a historical high fire year. The results are shown from the for 2-m temperature, with winds superimposed at 850 hPa in Figure 3 for the RCP8.5 future climate.

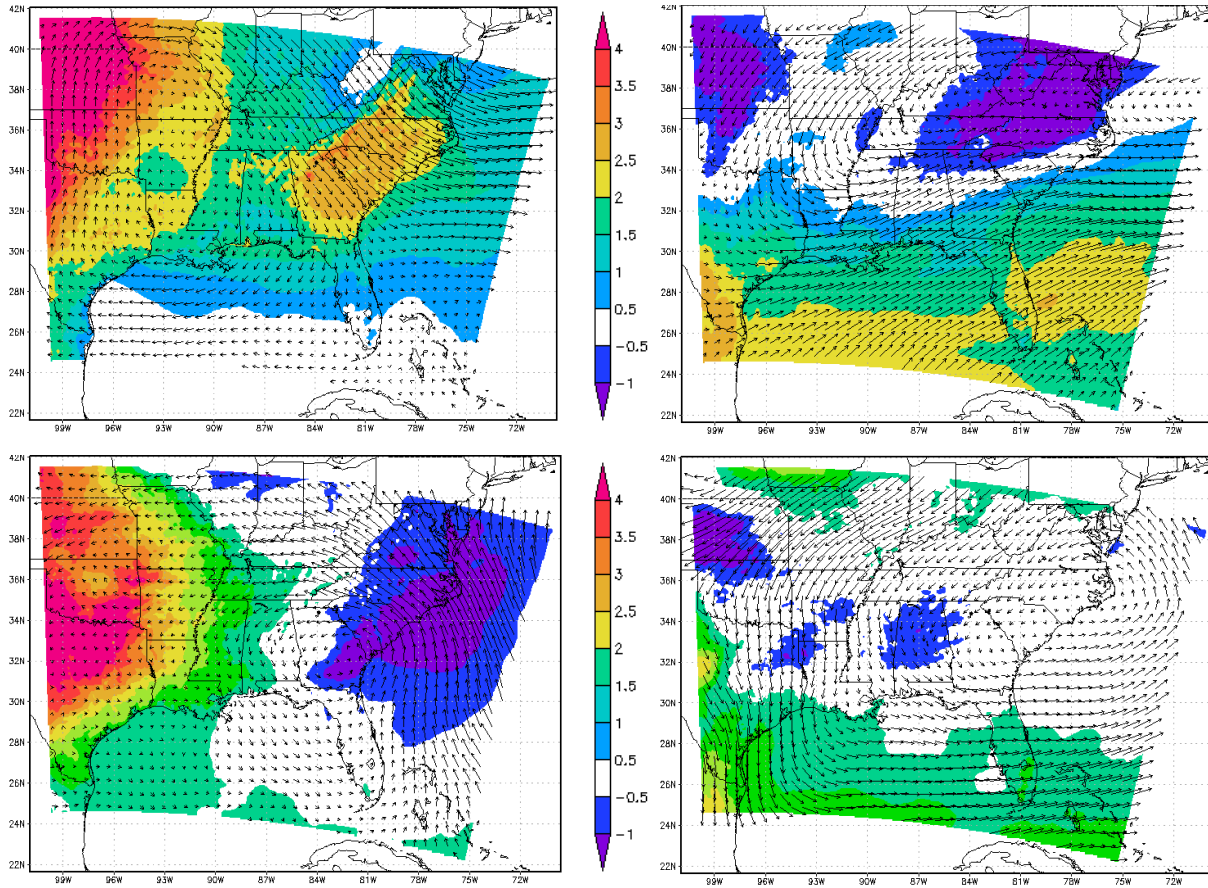


Figure 3. Differences in 2-m temperature between L – future high-fire and historical low-fire year; R - future low-fire and historical high-fire year. Top panels: GISSE downscaling; Bottom panels: CESM downscaling. Winds shown at 850 hPa.

This matrix of temperature difference maps represents both the uncertainty due to the natural variability of the Haines Index (L-R) and that of the two different GCMs (top-bottom). The upper left panel shows anomalous anticyclonic circulation with warming. The region from the Carolinas to Georgia has downslope flow off the mountains favoring larger regional warming. The upper right panel shows anomalous cyclonic circulation to the north and cooler conditions for much of the interior Southeast. The GCM uncertainty is shown in the differences between the top and bottom panels for each set of these differences; in these comparisons, the downscaled results from CESM show greater cooling compared to the GISSE downscaling domain-wide in going from historical to future climates, and less differences due to the natural variability (i.e., in the panels displayed left to right).

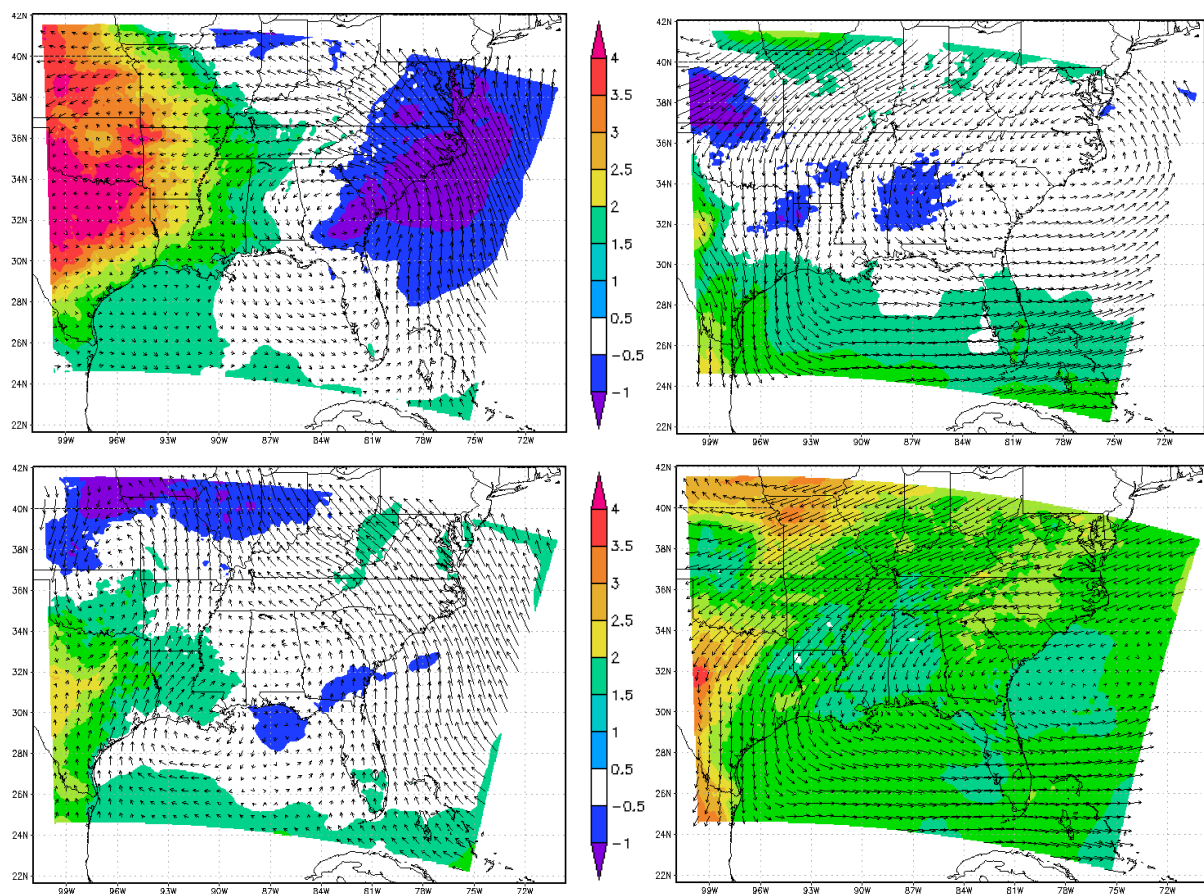


Figure 4. Differences in 2-m temperature downscaled from CESM between L – future high-fire and historical low-fire year; R - future low-fire and historical high-fire year. Top panels: RCP8.5; Bottom panels: RCP4.5. Winds shown at 850 hPa.

The uncertainty due to the RCP scenario assumptions is shown in Figure 4 for downscaling from the CESM. Note that natural variability seen in going from left to right is still a large source of uncertainty in the future, especially when considering a lower GHG emission scenario (RCP4.5; bottom panels).

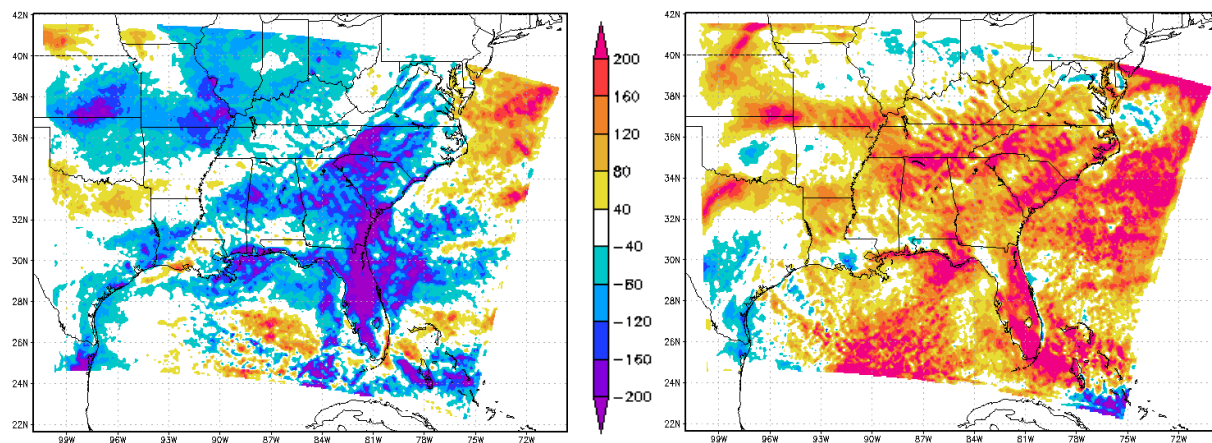


Figure 5. Differences in precipitation between L – future high-fire and historical low-fire year; R - future low-fire and historical high-fire year for downscaling from GISSE.

The left panel of Figure 5 shows the differences in precipitation between 2043 and 2001 for the anomalous anticyclonic circulation with drying, while the right panel shows anomalous cyclonic circulation, with the Southwesterly flow from the Gulf favoring wetter conditions near the Gulf Coast.

Overall these results suggest that the ensemble approach would capture a wide range in fire weather, with the western part of the domain (Texas, Oklahoma and Kansas) being likely to have more fires in the future decade compared to the historical.

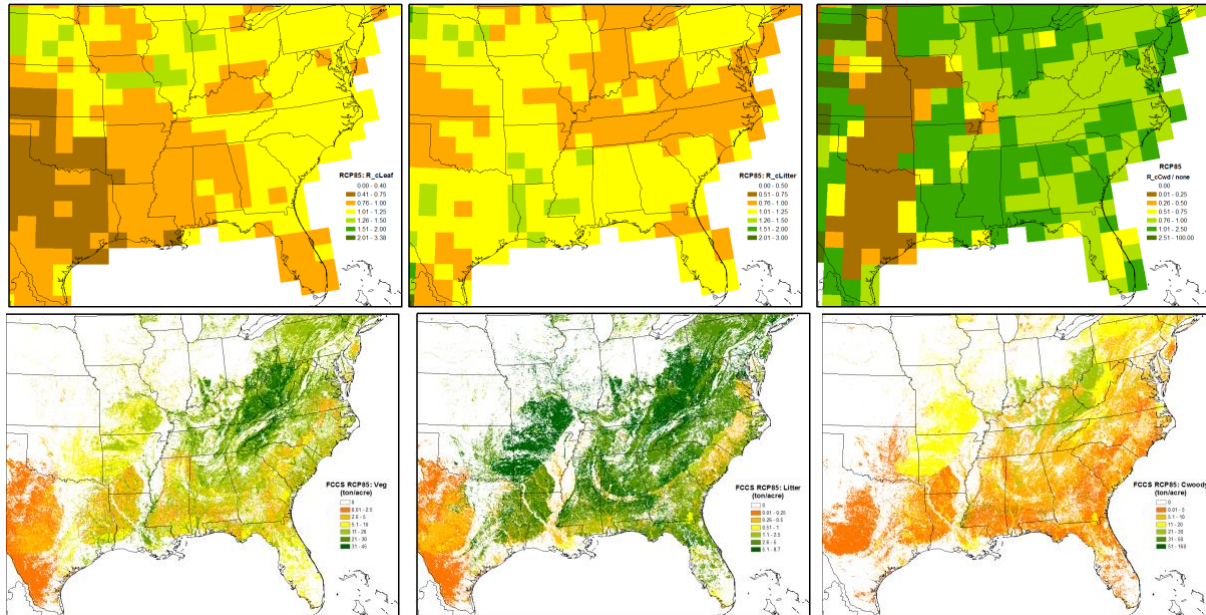


Figure 6. Future/historical biomass ratios in carbon compartment (upper panels) and future FCCS fuel loads (lower panels) for RCP8.5: L – leaf; C – litter; R – CWD. FCCS fuel loads represent the aggregation of all affected fuel categories in each carbon compartment.

Fuel load ratios future/historical are displayed in the upper panels of Figure 6 for the three carbon pools, leaf, litter and CWD for the RCP8.5 warming scenario. The lower panels show the corresponding tons/acre in each carbon pool aggregated over their respective fuel categories for the representative year (2045) in the future decade. The greatest tonnage was found to be in the leaf, followed by the CWD pools, and concentrated in the Appalachian region. Given the warming and drying predicted in some of our WRF ensemble simulations, this would be a region for increased fires in the future decade.

Wildfire PM_{2.5} emissions for the RCP8.5 and 4.5 scenarios and the two GCMs are shown in Figures 7 – 10 and provide an understanding of the intra-annual variability, and the impacts of GCM and RCP differences and natural variability on wildfire emissions for the RCP8.5 scenario.

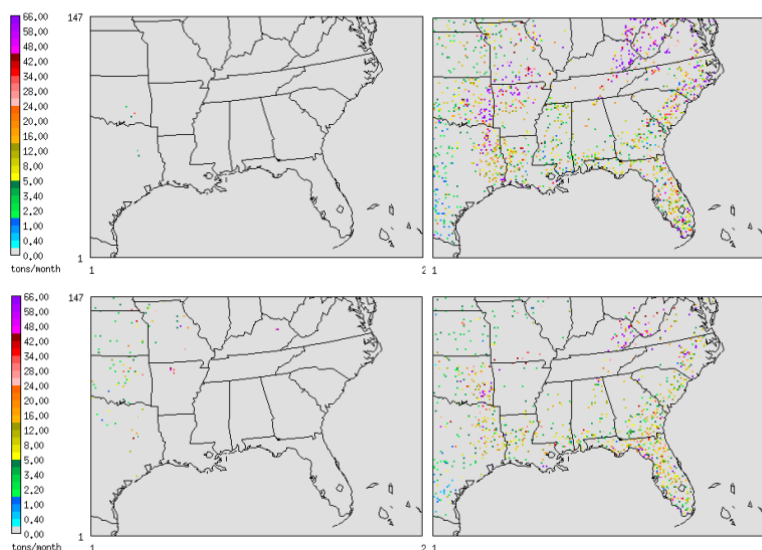


Figure 7. Monthly total wildfire PM_{2.5} emissions in 2043: L – March; R – July. Upper panels - downscaling from CESM; lower panels – downscaling from GISS.

Figure 7 shows that CESM tends to have more wildfire emissions than GISS in July, but that the opposite is true in March, and has more summer fires even in a low-fire year than does GISS in a high-fire year.

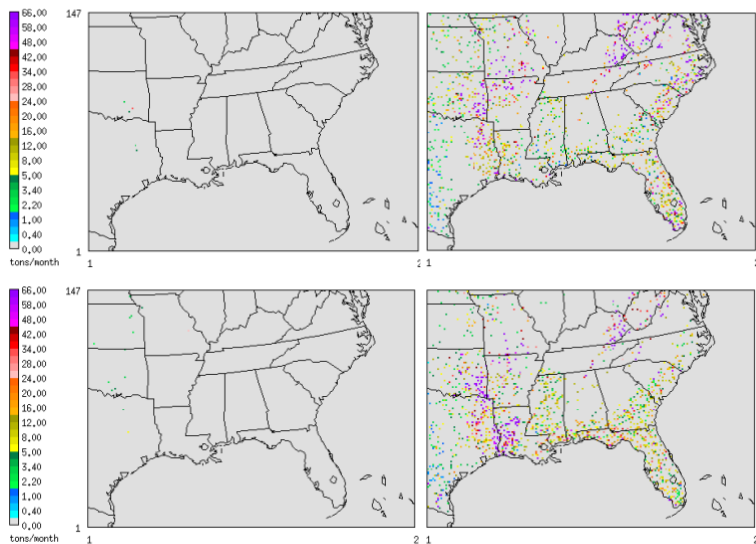


Figure 8. Monthly total wildfire PM_{2.5} emissions using dynamical downscaling from CESM: L - March; R – July. Upper panels – low-fire year (2043); lower panels – high-fire year (2041).

Figure 8 shows that the natural variability of the climate system (2041 vs. 2043) plays a less significant role in the emissions using CESM-downscaled meteorology compared to their intra-seasonal variability.

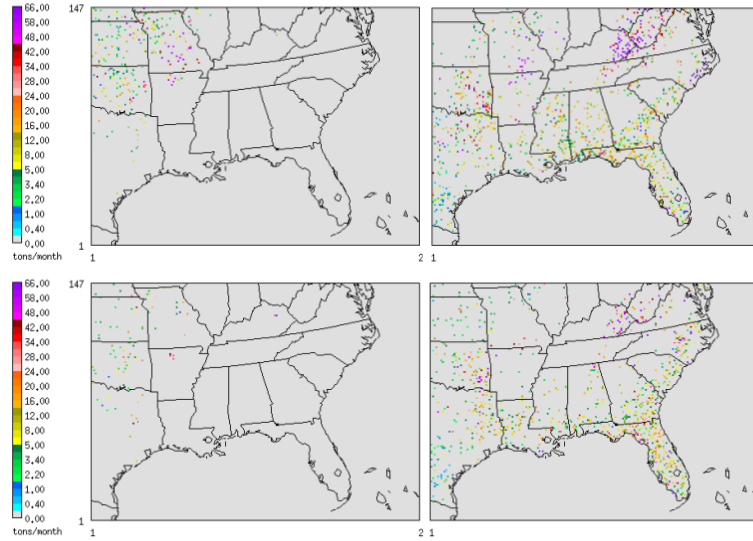


Figure 9. Monthly total wildfire $\text{PM}_{2.5}$ emissions using downscaling from GISSE: L – March; R – July. Upper panels – low-fire year (2045); lower panels – high-fire year (2043).

In the GISSE downscaling, the interannual variability of wildfire $\text{PM}_{2.5}$ emissions is somewhat more apparent, particularly in the cooler months. It is somewhat counterintuitive that the low-fire year as determined by the HI shows higher emissions in parts of the domain in the July totals. However, it should be noted that the HI was a global-scale screening tool to select the years with high fire potential, which may not be indicative of the trends in the mesoscale meteorology from which the FWI, the basis for these emissions estimates, is calculated.

Conclusions (Key Findings) and Implications for Management/Policy and Future Research

Although this project did not reach completion, it did provide useful insights in some key areas.

Findings

- The ensemble approach yields rich information in providing bounds on the uncertainty in regional climate change for impact assessments
- The low-level circulation anomalies in the future for the high fire weather potential years (large warming and drying) indicate a circulation change that would be consistent with a westward shift in the North Atlantic Subtropical High (NASH) (Li et al., 2012, 2013).
- WRF improves the representation of terrain and the localized warming and drying associated with the downslope flow off the Appalachian Mountains for the upper temperature extreme change.
- Our coarse-graining approach for estimating future fuels improves on using static values, as is done typically. However, uncertainties due to the spatial scale and lack of reliable vegetation-to-fuel correlations necessitate the ratio method rather than trying to capture raw fuel load values.
- It provides a new software tool that allows gridded FCCS fuel load data currently distributed with the BlueSky model to be modified to a future decade on the fly.
- The greatest fuel tonnage appears to be in the leaf and CWD pools, and is concentrated in the Appalachian region. Given the warming and drying predicted in some of the ensemble simulations, this would be a region for increased fires in the future decade.

Implications for Management/Policy

- The need for understanding how fires/emissions/ impacts will change in an evolving climate is not being addressed even in the best current wildfire emissions inventories. This work provides an approach to fill that gap and allow for better resource management and planning.
- The work is relevant to air and forest resource managers who need to prepare plans that include any future period, and atmospheric scientists in need of ensemble model results for the Southeast (our results will be archived in the Forest Service Research Data Archive by the end of this year).
- The tools developed for fuel projections may find application in prescribed burning decisions by facilitating what-if scenario assessments in different geographic areas targeted for fuel management.

Future Research

- A sensitivity analysis on the impact of static vs. dynamic fuel loads on future-year wildfire emissions would help assess the reasonableness of the ratioing approach for projecting fuel loads.

- Completing the ensemble simulations for future air quality will provide the impact assessments needed to extend this work to health studies.
- Addressing scale issues in fuel projections: fuel projections will always be a challenge because of the multiple facets of the problem (species-level changes in vegetation-to-fuel mapping being only one such). Given the uncertainty in fuel loads, doing a more thorough investigation of their representation in future wildlands, including hydrological considerations using the finer-scale representation they require, will be important.

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Appendix B: List of Completed /Planned Scientific/Technical Publications/Science Delivery Products

Publications

Prestemon JP, Shankar U, Xiu A, Talgo K, Yang D, Dixon E, McKenzie D, Abt K (2016) Projecting wildfire area burned in the south-eastern United States, 2011-2060. *International Journal of Wildland Fire* **25**, 715-729. <http://dx.doi.org/10.1071/WF15124>.

Presentations

Bowden JH, Talgo K, Ran L, Shankar U, Xiu A (2015) Assessing the Impacts of Climate Change on Future Wildfire Activity over the Southeast U.S. using Dynamical Downscaling. Poster presented at the *Meteorology and Climate-Modeling for Air Quality (MAC-MAQ) Conference*, Sacramento CA, September 15-18, 2015.

Shankar U, McKenzie D, Bowden J, Talgo K, Ran L, Baek BH, Adelman Z, Xiu A, Omary M, Adams EA, Yang D (2015) Reconciling Scales for Modeling the Effects of Climate Change on Wildfires. Presented at the Joint Assembly of the American Geophysical Union, Montreal, Canada, May 3-7, 2015.

Shankar U, Prestemon J, McKenzie D, Xiu A, Talgo K, Baek BH, Omary M, Yang D (2015) Statistical and Stochastic Model Applications for Projecting Wildfire Impacts on Southeastern U.S. Air Quality. Presented at the *Meteorology and Climate-Modeling for Air Quality (MAC-MAQ) Conference*, Sacramento CA, September 15-18, 2015.